CONTRIBUTION OF SURFACE MAGNETIC RECORDINGS TO PLANETARY EXPLORATION

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Abstract:

The transient variations of the magnetic field at the surface of a planet has a primary external source, the interaction between the environment of the planet and solar radiation, and a secondary source, the electric currents induced in the conductive planet. The continuous recording of the time variations of the magnetic field at the surface of Mars by means of three components magnetometers installed onboard landers would therefore allow to study both the interns/ structure of Mars and the dynamic of its ionized environment.

The depth of penetration of an electromagnetic wave in a conductive medium depends on both the period of the wave and the electrical resistivity of the medium. The larger the period and the resistivity, the greater the depth of penetration (skin effect). The high frequency spectrum will therefore enable one to estimate the resistivity in the uppermost kilometers of the planet, and to give information about the presence (or absence) of liquid water under the permafrost. The low frequency spectrum of the transient variations will give information on the presence (or absence) of sharp variations in the resistivity in the uppermost hundreds of kilometer of Mars, and thus on the thermodynamic conditions within the upper mantle of this planet.

Averages of the measurements made during 'quiet time measurements' would provide one with a very good estimate of the field of internal origin at the locations of the surface stations. If in addition we can expect a total duration of one year or more for the mission, and a drift on the order of 1 nT per year for the ground based magnetometer, we might even be able to detect some dynamo-related secular variation. /n addition to the map of the Martian magnetic field which will be produced by the Mars Surveyor 1 orbiter, these ground based local main field measurements will provide original information on the present and past magnetic field of Mars, and then on its present and past core dynamics.

As is the case for the Earth, different possible controlling plasma processes will lead to different convection patterns inside the magnetosphere and therefore different magnetic signatures at the planetary surface. Continuous recordings of the transient variations of the magnetic field onboard landers will then provide constraints on the convection within the Martian magnetosphere, that is a small magnetosphere where the ionosphere lies at great heights relative to the dimensions of the magnetospheric cavity.

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1. INTRODUCTION

The internal structure of a planet may be described, as a first approximation, using few independent physical parameters, such as the velocity of propagation of acoustic waves, the density, the magnetic susceptibility or the electrical resistivity. In the case of the Earth, the study of these parameters provided an early relevant description of the major features of the planet (solid inner core, liquid conductive outer core, Moho discontinuity at the crust-mantle boundary, conductive layer at the asthenosphere-lithosphere boundary,....). The knowledge of these parameter distributions in the Mars interior would similarly provide an accurate first-order global description of the internal structure of the planet.

The investigations can be made with methods involving either natural or controlled sources. The latter methods use artificial fields, created by devices whose spatial-temporal parameters are known (e.g., electric or magnetic dipole). The depth of investigation depends on the injection device characteristics among others. Tremendous problems (source of energy, dimensions of the transmitter, dimensional stability of receivers,...) arise when setting up soundings to probe targets of kilometric extent, or even greater ones. Hence, natural signals are worth being used as sources for planetary exploration by means of geophysical techniques, even though uncertainties remain as to their behavior, as it is the case for Mars.

The magnetic field of a planet may result from two primary sources, convection in a conductive liquid core and the interaction between the planet and solar wind plasma, and from two secondary sources, the local magnetization of crustal and lithospheric rocks and electric currents induced in the planet by the transient magnetic fields of external origin. The study of the magnetic field of a planet would then provide original information in various domains, as its past and present core dynamics, its lithospheric past evolution and present structure, or the electrodynamics of its ionized environment. The results obtained in the case of the Earth strikingly illustrates possible contributions of magnetism to planetary exploration [see, e.g., *Jacobs* (1987; 1988; *1989;* 1991)].

The time and space constants of the magnetic fields related to these different sources are very different, and different complementary experiments are then necessary to completely investigate the magnetic field of a planet:

- the field due to magnetization of crustal rocks is characterized by geological scale time constant, and spatial scales ranging from a few kilometers, and even less, to a few thousands of kilometers. Profiles with magnetometers onboard balloons *(Cohen et al., 1986)*, or maps with low altitude satellites *(Cohen and Achache, 1990; Acuña et al.,* 1992) are then suitable tools for studying this field. On the other hand, in situ measurements with a flux-gate magnetometer and a magnetizing coil onboard a lander would allow one to investigate the magnetic properties of surface materials *(Nielsen et al., 1992);*

- the intrinsic planetary field, if any, extends at a planetary scale, and its geometry can be easily described by means of satellite maps *(Langel, 1985; Lange/ and Estes, 1985; Acuña et a/., 7992).* Its variations with time are in the order of a few tens of nT per year on the Earth, and surely on the order of, or even smaller than few nT per year on Mars. The measure of such small changes may then be very difficult to achieve, because it requires long-term, precise recording of the magnetic field onboard satellites or ground stations;

- the transient variations on the Earth result from both the interaction between the planetary environment and the solar wind plasma (primary source), and induction in the conductive planet (secondary source). They are characterized by time constants ranging from a few tens of seconds to a few days, and space wavelengths ranging from a few tens of kilometers to the hemispheric scale (Jacobs, 1991). Nothing is known about their time and scale constants at the surface of Mars, but they are likely not to be different than those observed on the Earth. Continuous recordings during a few months of the transient variations of the magnetic field at a network of stations distributed at the surface of Mars will therefore allow one to obtain a first description of the transient magnetic field, and then provide information on both the inner structure and the electrodynamics of the ionized environment of Mars.

Ground based recordings of the time variations of the magnetic field at the surface of the planet are then necessary to achieve the magnetic exploration of a planet, and in particular that of Mars. Such measurements are planned to be made onboard the two Small Autonomous Stations to be installed at the surface of Mars as part of the Russian Mars 96 mission (OPTIMISM/MAG experiment). Measurements will be made with low-mass, low-power consumption, three component flux-gate magnetometers with a resolution of 0.25 nl.

The OPTIMISM/MAG experiment is a first step, with limitations arising in particular from the amount of transferred data. It is then desirable to have this experiment followed by magnetic field variation recording onboard the INTERMARSNET landers. The example of the Earth shows that having simultaneous recordings at the surface of the planet and onboard the orbiter would likely greatly improve the scientific return of the surface magnetic experiment, and it would then be desirable to also have, three component magnetometer orrboard the INTERMARSNET orbiter.

We discuss in the present paper the possible contribution of magnetic recordings onboard landers operated at the surface of Mars. We briefly review in section 2 the present knowledge on the magnetic field of Mars, then discuss in section 3 the scientific objectives of the experiment. The proposed experiment is described and discussed in section 4.

2. THE MARTIAN MAGNETIC FIELD

Some knowledge of the magnetic field of Mars was obtained through the data collected by the American Mariner-4, -9, and Viking spacecraft, and the Soviet Mars-2, -3, and -5 missions. Bow shocks crossings have been detected at distances between 1.5 and 3 planetary radii *(Smith et al., 1965; Smith, 1969; Dolginov et al., 1976).* The the observations also suggest that the dayside polar cusps are located at very low latitudes *(Siscoe,* 1978; *Intriligator and Smith, 1979),* and that the shocked solar wind plasma has direct access to the ionosphere through these regions. During the descent of the Viking landers, peak ionospheric densities of -10' cm"' have been measured at an altitude of 130 km above the planet's surface *(Stewart* and Hanson, 1978). More recently, our understanding of the magnetic field of Mars, and of the Martian environment in general, has benefited from information gathered by the Soviet Phobos-2 spacecraft, which approached the Martian surface within 850 krn in February-March 1989 [for a review of recent works, see e.g., *Luhmann (1991)* and *Luhmann and Brace (1991)].*

2.1 Constant or slowly varying field

The constant or slowly varying part of the magnetic field of a planet results from the convection in the liquid conductive core and /or the magnetization of lithospheric rocks.

- the convection in the core is the primary source. Chemical differentiation processes in the planetary core and the planetary rotation may give rise to an active internal dynamo which generates the internal main planetary field;

- the magnetization of crustal or lithospheric rocks is the secondary source of the slowly varying part of the magnetic field. It may either result from the fossilization of the magnetic field at the time of formation of the rocks (remanent magnetization) or be induced by the present planetary magnetic field (induced magnetization).

In the case of the Earth, the core dynamo is still active and generates a quasi-dipolar field with a dipole moment of 810'5 Tm^3; in the case of the Moon, the presence of strong remanent magnetization indicates the existence of an active core dynamo in the past *(Merrill and McElhinny,1983).* Mars is intermediate in many respect between the Moon and the Earth, but we still have no clear indications about the present and past intensity of the main Martian planetary field.

Data from the Phobos probe suggest that the magnetic field at the surface of Mars is about 30 nT at the equator *(Riedler et al.* 1989; *Möhlmann et al., 1991).* The weakness of the Martian planetary field results in a situation where the obstacle encountered by the solar wind is both the planetary magnetic field and the ionoshere, and even the neutral atmosphere in presence of strong perturbation from the interplanetary medium.

2.2 Transient field

The transient variations of the magnetic field at the surface of Mars has a primary external source, the interaction between the environment of the planet and solar wind, and a secondary source, the electric currents induced in the conductive planet,

At a given station on the surface of a planet, one part of the observed transient variations of the geomagnetic field is due to currents induced in the conductive solid planet, which depend on the distribution of conductivity in the planet. However, it can be shown in the case of the

Earth that the effect of induced currents on the variation of the horizontal geomagnetic field can be described by a first order approximation with a multiplicative factor. This factor does not differ by more than about 10% from one station to another, except in the case of sharp local heterogeneities of the conductivity in the crust and the upper mantle. The same situation will likely prevail for Mars, and the transient variations observed at the surface of the planet can be considered as the signature of the currents taking place in the entire ionized environment of the planet, under the influence of the solar wind.

Little is known about the behavior of the magnetic field due to currents flowing in the ionized environment of a planet like Mars. The exact nature of the interaction between the solar wind and the high ionosphere is still unknown because of the lack of adequate observations. Whatever physically takes place, this interaction will result in a transfer of momentum from the solar wind to the plasma originating from Mars on the sunward and duskside of the planet.

In the dynamo region of the ionosphere, located at an altitude of about 130 kilometers according to Viking data, plasma movement gives rise to currents similar to those observed at high latitudes on the Earth. Of course, in absence of any measurements or theoretical models, it is impossible to give a precise order of magnitude of their intensity and of the magnetic perturbations resulting at ground level: a value on the order of the planetary field, that is 10-30 nT is probably a maximum. As to their temporal characteristics, they must be close to those observed in auroral and polar magnetic activity on the Earth (Figure 1), since the source (solar wind fluctuations) and the spatial-temporal filter effect of the conducting ionosphere are similar. Time characteristics of 30-60 seconds seem realistic.

Currents generated in the transition zone, between the solar wind and the ionosphere, are difficult to evaluate. So is their influence on the magnetic field at the surface of the planet. If the terrestrial magnetopause is taken as a reference for an order of magnitude, then perturbations of 10 to 20 nT are obtained. The latter have time characteristics close to 30 to 60 seconds since they originate from the velocity fluctuations of the solar wind, and from the variations of the interplanetary magnetic field (IMF).

Qualitative considerations therefore show that the different current systems which may exist must induce magnetic field perturbations at the surface whose maximum amplitude ranges between 10 to 20 nT, with typical variation times greater than 30 to 60 seconds. The morphology of the magnetic variations at the surface of Mars is expected to be intermediate between those of the IMF and those resulting from the Earth environment filter (Figure 1).

3. SCIENTIFIC OBJECTIVES

The scientific objectives of continuous magnetic recordings at the surface of Mars, in order of priority, are to (1) probe the internal structure of the planet by means of electromagnetic sounding methods, (2) characterize the time variations of the planetary magnetic field of Mars, and its spatial variations if measurements are made during the descent phase, and (3) investigate the space and time characteristics of the magnetic field sources in the ionized environment of Mars.

3.1 Study of the internal structure of the planet

The internal structure of Mars will be investigated by means of magnetic sounding methods. These techniques, which give an image of the distribution of the electrical resistivity within the planet, are based on the analyses of the transient variations of the magnetic field recorded at the surface of the planet. They are commonly used to probe the internal structure of the Earth, and significantly contributed to the present understanding of the terrestrial crust, lithosphere and upper mantle structure and dynamics [see e.g., *Hjelt and Korja (1993)* and *Tarits* (1994) for reviews].

The depth of penetration of an electromagnetic wave in a conductive medium depends on both the period of the studied phenomenon and the medium's electrical resistivity where the sounding is carried out. It varies proportionally with the square root of the period-resistivity product, and the larger the period and the resistivity, the greater the depth of penetration (skin depth). The depth to which electromagnetic sounding probes then increases with decreasing frequencies, and the analysis in the frequency domain of the electromagnetic field variations allows one to have information on the mean variation with depth of the electrical resistivity below the station. The high frequency spectrum bears information on the resistivity profile in the uppermost kilometers of the planet, and the low frequency spectrum enables one to probe it down to a few hundreds of kilometers in depth.

3.1.1 Ice deposit and presence of conductive fluids

The determination of the mean resistivity profile in the uppermost kilometers of the planet will allow one to estimate the thickness of the resistive permafrost, and to have information about the presence (or absence) of liquid water under the permafrost.

The resistivity of cold dry rocks is very high, generally on the order of, or greater than, a few tens of thousands of Ω.m. In presence of a conductive liquid phase, the resistivity sharply decreases. Adopting an effective resistivity ρ^* as an approximation to the actual resistivity of the crust in such a situation. we will find that it is related to the resistivities of the liquid and solid phases through:

$$\frac{1}{\rho''} = \frac{\frac{1}{\rho^l} - \left(\frac{1}{\rho^l} - \frac{1}{\rho^s}\right)\cdot\left(1-\frac{2f}{3}\right)}{1+\frac{f}{3}\left[\frac{\rho'}{\rho'}-1\right]}$$

where ρ' and ρ'' are the resistivities of the liquid and solid phases respectively, and f the percentage of liquid. This relation may be simplified when $\rho^s >> \rho^l$, as it is the case in the crust where the solid and liquid phases consist respectively in cold dry rocks and water rich fluids:

$$\frac{1}{\rho''} = \frac{2}{\rho'}\,\frac{f}{3-f}$$

The resistivity of water rich fluid being on the order of a few Ω.m, the effective resistively falls down to values on the order of a few tens of Ω.m in presence of 1% of water rich fluids. As the resistivity of the permafrost is very high, the presence of liquid water at the bottom of the permafrost will then correspond to a decrease of the resistivity by two or more orders of magnitude (Figure 2). Electromagnetic sounding is then very well suited for detecting the presence of liquid water in the Martian crust,

3.1.2 Conductive structure of the planet

The low frequency spectrum of the natural field will give direct estimation of the impedance Z and then of the material's resistivity of the Martian lithosphere and mantle, down to a few hundreds of kilometers in depth. The study of the internal structure of Mars by means of electromagnetic sounding methods is one of the major aims of a magnetic experiment onboard landers.

Electromagnetic studies have extensively been made on the Earth for decades, in both continental and oceanic domains. Results indicate that the electrical resistivity structure of the crust and upper mantle is deeply related to the nature, age, and tectonic history of the lithosphere.

The resistivity is essentially dependant of the metrological nature of the materials and the thermodynamic conditions, The laboratory results on terrestrial materials [see e.g., *Shankland and Waff (1977), Olhoeft (1980), Parkhomenko (1982),* and *Shankland and Ander (1983)*] show that the electrical resistivity varies greatly with respect to the thermodynamic conditions such as the temperature T and the percentage of conductive fluids within the solid matrix (molten rocks, water rich fluids). For non-hydrated rocks, the resistivity remains very high for temperatures up to 1200°C or even 1800"C in some cases. Molten rocks have low resistivities (1-0.1 Ω.m) and in the presence of partial melting, the effective resistivit y falls sharply by several orders of magnitude at constant temperature (Figure 3). Electromagnetic soundings will thus determine the presence (or absence) of partial melting at the base of the lithosphere. The electrical resistivity is also very sensitive to minor constituents of the Earth lithosphere, such as carbon/graphite, saline fluids, and small percentages of partial melt, that are closely related to present and past geodynamic processes [see e.g., *Hjelt and Korja (1993)* for a review].

Electromagnetic studies demonstrate that the Earth's lithosphere has a very complicated electrical structure. In tectonically active regions, for instance, partial melts and free saline fluids form conducting structures that are distinct for different tectonic environments (e.g., continental rifts, mid-ocean ridges, oceanic subduction zones and convergent continental margins). In stable regions ancient tectonic processes have left in many places electrically conducting traces which give information, for instance on collisions of either continental or island arc crustal blocks, revealing the location of paleosuture zones.

It however appeared that different mean resistivity structures are associated with major tectonic regions: stable Precambrian shields and platforms, younger stable regions, currently active regions such as collisional zones or extensive basins. In the oceanic domain, the resistivity profile in the lithosphere is directly related to the age of the plate [see e.g., *Tarits and Jouanne (1990)]*.

The electrical structure of the Earth lithosphere and upper mantle can then be described in terms of average models depending on the overall tectonic history of the region, with heterogeneous structures that mark present or past geodynamic structures. One can expect that a similar situation prevails for Mars. The electromagnetic lithospheric probings made in the frame of the next missions to Mars (Mars 96: OPTIMISM/MAG experiment, and INTERMARSNET) would then mainly aim to characterize the mean conductive structures corresponding to different geological situations.

Little is known about the Martian lithosphere and upper mantle. The lithosphere of the Earth is resistive, and so it may be expected that the lithosphere of Mars has similar properties. The thickness of the Martian lithosphere may vary from a few tens of kilometers in the region of Tharsis to more than a hundred kilometers below Olympus Mons and Elyseum Mons. Almost nothing is known about the Martian upper mantle.

At greater depths, the increase in temperature and pressure corresponds to a rapid decrease in resistivity (on Earth, at approximatively 400 km). The probable existence of natural variations of the magnetic field of Mars at periods corresponding to the Martian day (24h37') should permit the localization of a sharp variation in the resistivity at four to five hundred kilometers in depth, if any, and thus derive information on the thermodynamic conditions within the upper mantle of Mars.

3.2 Study of the planetary field

The temporal and spatial behavior of the planetary field is directly related to the core dynamics and thermodynamics. The knowledge of both the magnetic field and its secular variation at the planetary scale is necessary to elucidate the core behavior from magnetic measurements. Results obtained during the last decade for the Earth gives a striking illustration of the contribution of magnetism to the understanding of the core behavior [see e.g., *Whaler and Clarke (1988), Bloxham (1989), Gire and Le Mouël (1990)* and *Hulot and Jault (1995)]*.

Mars is at present the only terrestrial planet for which definitive magnetic field measurements have not yet been made. The upcoming missions Mars 96 and Mars Surveyor will likely provide a relevant global mapping of the Marlian planetary magnetic field, but not any indications of its secular variation. Continuous recordings at a surface station with low drift magnetometers are necessary in practice to get estimates of, or at least bounds on the secular variation of the Martian planetary magnetic field. Given the fact that Mars is quite comparable to the Earth with respect to a number of parameters (size, likely conductivity of the core, duration of the day,...) that control the time scales of possible dynamo action, a secular variation on the order of a few nT/year is not unrealistic, especially if the planetary field is not mainly dipolar but involves higher degrees.

The length scales involved in the internal magnetic field are also a very important parameter to be determined. Whereas long length scales are compatible with both dynamo action and permanent magnetization, dominant very short length scales can only be the signature of remanent magnetization.

Continuous magnetic recordings onboard INTE.RMARSNET landers during surface operations, and if posible during the last stages of the descent phase will then provide information on the time and space variations of the Martian planetary. These information will complement the results of the Mars Surveyor (orbiter) and Mars 96 (orbiter and landers) future missions, and provide further constraints on the internal properties of Mars, and more generally to the dynamo theory in the case of small size planets in rapid rotation *(Levy,* 1976)

3.3 Ionized environment of the planet

The nature of the interaction between the solar wind and the planetary environment will strongly influence the properties and dynamics of both Mars' magnetosphere and ionosphere. The solar wind interaction is likely to be unique as compared to that of the ether planets. The martian field is weak (see section 2.1) and the resulting small magnetosphere will have many unique features. Its dynamics may be thoroughly dominated by convection driven by the solar wind, possibly leading to aurorae at relatively low latitudes and to a strong coupling to the upper atmosphere.

The magnetopause location is expected to be highly variable due to solar wind dynamic pressure variations, magnetic reconnection, and local instabilities. During high speed solar wind streams when the dynamic pressure can be an order of magnitude higher than its nominal value, the magnetopause will be pushed inward to lower altitudes and will probably be very close to, and even at the same altitude as the top of the ionosphere. Thus, during these intervals, the solar wind interaction may be more ionospheric or Venuslike than at other times.

Magnetic reconnection between interplanetary and any intrinsic planetary fields leads to the inward erosion of the magnetopause and tailward convection of field lines. This process may be controlled by plasma processes both within the magnetosheath and the ionosphere. As is the case for the Earth, different possible controlling plasma processes will lead to different convection patterns inside. the magnetosphere and therefore different magnetic signatures at the planetary surface. Continuous recordings of the transient variations of the magnetic field at the surface of the planet will then provide constraints on the convection within the marfian magnetosphere, that is a small magnetosphere where the ionosphere lies at great heights relative to the dimensions of the magnetospheric cavity.

During the intervals when the solar wind interaction is more ionospheric or Venuslike, dayside and nightside observed transient variations are expected to be very different. Dayside variations will provide information on the energy transfer from the solar wind to the ionosphere, and on the related ionospheric behavior. They will also indicate if Venuslike fluxropes exit, and are able to penetrate the magneto-ionopause down to low altitudes. Nightside variations will provide information on the nightside magnetopause and magnetotail curents systems, and will put constraints on the formation of the Mars magnetic tail discovered by Mars-5 *(Dolginov et al., 1976).*

4. THE PROPOSED Experiment

The magnetometers to be installed onboard each of the Intermarsnet landers are three component flux-gate magnetometers which will provide rapid (up to 20/sec.), precise (0.1%) and very sensitive (1 DU = 0.016 nT) vector measurements of the magnetic field variations observed at the surface of Mars, and if possible during the Mars surface approach and landing. The magnetometer has a wide dynamic range, in practice 4 ranges from ± 128 nT to ± 65536 nT with the upper range for instrument testing at the Earth. The sensor will be mounted at the end of a boom of about 2 meters length to minimize possible DC and AC lander-generated fields.

4.1 Data acquisition

During the approach and descent phases, the magnetometer will be, if possible, operated to study the magnetic field of Mars. It might then begin continuous data collection starting 1 day before landing, with the following operational profile:

- from t_0 - 24h to t_0 - 8h (t_0 being the expected landing time), three-component vector measurements with a 60 second sampling rate (data rate: 1/60 sps);

- from t_0 - 8h to t_0 - 3h, vector measurements with a 4 second sampling rate (1/4 sps);

- from t_0 - 3h to t_0, vector measurements with a 1/20 second sampling rate (20 sps).

After landing and deployment of the boom, vector measurements will be routinely made on a continuous basis with a 30 seconds sampling rate (1/30 sps), with occasional high frequency samples with a 1/20 second sampling rate (20 sps), each of 15 minutes in duration. This would allow the study of the magnetic field variations, and the derivation of the impedance Z for frequencies ranging from a few Hz to a cycle per day and even below, the limitation in the low frequency range arising from thermally driven drifts of the magnetometer.

4.2 Data processing

The data will be transfered back to the Earth without any in situ processing, except data compaction. Different data processing will be then applied, depending on the scientific objectives of the studies.

4.2.1 Study of the internal structure of the planet

The resistivity distribution within the Earth is usually determined by the magnetotelluric tensor which relates, in the frequency domain, the horizontal component of the electric field to that of the magnetic field simultaneously recorded at a station. When (i) the resistivity varies with depth only, and (ii) the externally originating variations are, as a first approximation, homogeneous at the scale of the studied area, the impedance tensor is antisymmetric; the antidiagonal terms are equal to plus or minus the transfer function Z between the magnetic and electric fields, respectively. Z is called the impedance of the conductive medium. This transfer function is directly related to the variation with depth z of the resistivity, and information about the resistivity profile can therefore be deduced from the observed variation of Z in the frequency domain. We will estimate the more likely resistivity profile, and its confidence interval with inverse methods based upon the Bayesian technique.

4.2.1.1 Impedance derivation

When the resistivity only varies with depth, the impedance Z may also be deduced from the ratio of the vertical component of the magnetic field and the horizontal gradients of its horizontal component, The function Z may therefore be deduced from recordings made simultaneously at at least three stations located at the points of a triangle. The horizontal gradients are computed between the stations, that will then give an estimate of the mean impedance at the scale of the studied area. For the Earth, this method was successfully used by (Jones, 1980) to derive the impedance Z over the Scandinavian shield.

The resistivity distribution within the planet may also be deduced from the ratio, in the frequency domain, between the horizontal and vertical components of the magnetic field at a given station, provided the geometry of the sources is known. For the Earth, this method was successively applied by *(Schultz and Larsen, 1987)* using the axisymmetric ring current field, for which the source geometry (P_0^1) is well known. In the case of Mars, this method might allow one to derive information about the resistivity distribution if only one or two stations are operating, or if the distribution of the station at the surface of the planet does not allow reliable estimates of the gradients.

Note that several networks evenly distributed over the planet would allow the global determination of the mean variations of the resistivity with respect to depth, and the study of the eventual lateral resistivity variations. Furthermore, the comparison between different profiles made at different locations will provide information about the relations between the inner structure of the planet and the surface geology.

4.2.1.2 Error estimates

Let us address now the question of the accuracy of the impedance estimates deduced from recordings of magnetic variations alone. When three stations or more are available, estimating the impedance does not require the knowledge of the geometry of the sources. It is in fact straightforward to derive from the Maxwell equations that:

$$Z = i\omega\mu_0 \frac{H_z}{\frac{\partial H_x}{\partial x} + \frac{\partial H_y}{\partial y}}$$

where H_u is the component of the magnetic field along the direction u; x and y corresponds to perpendicular horizontal directions, and z to the vertical direction.

The magnetotelluric approximation is the limit case where the wavelength of the source is large compared to the penetration depth in the conductive medium. The primary field can then be described as a plane wave, and the magnetotelluric situation corresponds in fact to the plane wave approximation. In the case of the Earth, experimental results show that the impedance Z does not significatively depend on the wavelength of the external field, provided this wavelength remains greater than a few thousands of kilometers. One can expect that the same situation prevails for Mars, thus allowing an accurate estimation of the magnetotelluric impedance of the planet with magnetic recordings at a network of three stations.

The stations ideally should be installed at the points of an equilateral triangle. The currents flowing in the ionized environment sources are directly related to the interaction at planetary scale between the Martian environment and the solar wind. A station spacing between a few hundreds and a few thousands of kilometers would then likely ensure accurate estimates of the impedance with measurements of 0.1 nT resolution.

On the contrary, the determination of the impedance with magnetic recordings from a single station requires the knowledge of the geometry of the source. Because the air above the planet's surface can be considered as nonconductive, it is convenient to express the electromagnetic field between the planet and the ionosphere conductive shell in terms of harmonic potential functions. In the spherical case (r, θ, ϕ coordinates), the elementary potential functions are the $S_n^m(\theta, \phi)$ functions, and the relation between the impedance and the ratio of the vertical (H,) to the horizontal (H_h) component of a magnetic field is for the harmonic of degree n and order m:

$$Z = \frac{H_r}{H_h} \cdot \frac{i\omega r}{n(n+1) S_n^m} \cdot \left[\left(\frac{\partial S_n^m}{\partial \theta} \right)^2 + \left(\frac{\partial S_n^m}{\partial \phi} \right)^2 \right]^{1/2}$$

The uncertainties in the determination of the geometry of the external sources using recordings from orbiters and only one or two ground stations may therefore affect the determination of the impedance Z

In order to quantify the bias which may result from errors in the determination of the geometry of the source, let us consider the case of a stratified tabular medium (x, y, z cartesian coordinates; z vertical) for which the calculations are more simple. In that case, the elementary potential functions are:

~2m[kx(x-xo},k,(y-ye)]

where k_x and k_y are the wavelength numbers. The source geometry of such an elementary field is described by four parameters: k_x, k_y, x_0 and y_0. Errors in the description of the geometry then correspond to errors in the determination of these parameters. The relation between the impedance and the ratio of the vertical (H_z) to the horizontal (H_h) components of a magnetic field is, for the elementary potential function we consider:

$$Z = 2i\pi \frac{H_z}{H_h} \frac{i\omega\mu}{(k_x^2 + k_y^2)^{1/2}}$$

Let Au be the error on the parameter u. The relative error in the impedance determination resulting from errors in the determination of the source geometry is then equal to:

$$\frac{AZ}{Z} = \frac{k_x^2}{k^2} \frac{\Delta k_x}{k_x} + \frac{k_y^2}{k^2} \frac{Ak_y}{k_y}$$

where $k^2 = k_x^2 + k_y^2$. This means that the relative error in the Impedance determination is in the order of the relative error in the source wavelength determination.

The example of the Earth shows that the source wavelength can be determined with fairly good precision from the morphological analyses of the transient variations of the magnetic field because events of similar morphology are related to the same processes in the Earth ionosphere and magnetosphere. It is likely to be the same for Mars, and one can expect to derive a fairly accurate estimates of the source wavelength from statistical and morphological analysis of the observed transient variations.

4.2.2 Study of the planetary field

It is clearly impossible to describe a phenomenon of planetary extent with data from few stations more or less evenly distributed at the surface of the planet. The magnetic variations recorded during the surface operations and, if possible, during the descent phase would however allow the characterization of the temporal and spatial variations of the constant or slowly varying planetary magnetic field of Mars.

4.2.2.1 Surface data

If it exists, the planetary field is likely to be time independent (remanent magnetization) or slowly time-varying (dynamo field), in contrast with the transient variations which are likely to be modulated on a daily or shorter basis. Defining ‘quiet time measurements’, and deriving daily, weekly, or monthly averages of the ground field, as it is currently done in geomagnetic observatories would already provide us with a very good estimate of the field of internal origin. If in addition we can expect a total duration of one year or more for the mission, and a drift on the order of 1 nT per year for the ground based magnetometer, we might even be able to detect some dynamo-related secular variation.

4.2.2.2 Descent phase data

Given the fact that the final approach of the lander, below the ionospheric layers, would be slow and that it would probably encounter significant winds, we may expect some large enough horizontal displacements during the crossing of the atmospheric layers. If the magnetometer could record during this final parl of the approach of the lander, a faily *long low* altitude profile could be derived. Analysing this profile along the same lines as those used to analyse low altitude magnetic profiles above the Earth *(Cohen et al., 1986)* will provide original information on characteristic values of the horizontal and vertical gradients of the planetary magnetic field close to the landing sites.

4.2.3 Study of the external sources

The example of the Earth gives a striking illustration of the possible contribution of permanent recordings at the surface of a planet to the study of its ionized environment. Up to the end of the 1950's, the only available data to investigate the ionized environment of the Earth's were in fact recordings of the transient variations of the Earth magnetic field made at ground stations. The extensive study of these variations led to postulate the existence of external currents sytems in the Earth environment (S_R and S_q currents, ring current, tail currents, magnetopause currents, DP2 currents, substorm currents, field-aligned currents and auroral electrojets.. ..) and to describe the main space and time characteristics of their sources.

4.2.3.1 Surface data

The knowledge of the variations of the geomagnetic field at ground stations alone does not enable one to determine the 3-dimensionnal distribution of these currents. Nevertheless, assuming a perfectly resistive atmosphere between the conductive Earth and ionosphere, if is possible to account for the observations in terms of gradient of a scalar harmonic function. The upward continuation of this function up to the ionosphere conductive shell provides the gemetry of the ionospheric equivalent currents. Thses currents are the only information which can be derived from ground-based stations taken alone, without further hypothesis.

Ionospheric currents circulating in the E region account for most of the variation in the Earth's magnetic field. The relationship between these variables can be derived from Ampere's law. It was put forward by *(Chapman and Bartels,* 1940):

$$|\Delta B| = (2\pi/10 f)|J|$$

where B is expressed in nanoTesla (nT) and J in $A.km^{-1}$. It is a corrective factor that takes ground current effects into account. It is usually taken equal to 0.6 [see e.g., *Kamide and Brekke (1975)]*.

Nothing is known about the geometry of the external sources of the Martian magnetic field. In fact, this is one of the aims of the magnetic experiment onboard landers during the nexi Martian exploration missions.

4.2.3.2 Descent phase data

The solar wind interaction is likely to produce a significant distortion of the weak planetary field. Because of the small scale of the magnetosphere, currents associated with the solar wind interaction will be relatively close to the planetary surface. For example, on the dayside the magnetopause is expected to lie between 400 and 1000 km altitude, depending on solar wind conditions, and on the night side, the magnetotail current sheet will probably extend inward to approximately the same altitude range. Before the Phobos 2 spacecraft, all spacecraft which hitherto carried a magnetometer did not come closer than =1100 km above the martian surface. The trajectory of Phobos 2 allowed for the first time the collection of data down to 850 km above the dayside surface of Mars, in regions which are relevant for the solar wind-Mars interaction investigation.

Phobos 2 magnetic field measurements show that the martian bow shock, magnetosheath, and planetopause have clear magnetic signatures *(Riedler et al., 1991)*. When approaching the planet from the interplanetary medium, the field magnitude becomes increasingly turbulent, showing generally a distinct jump. After the jump, the level of turbulence increased, then the fluctuations suddently disappear. *Riedler et al. (1991)* identified the jump as the bow shock crossing, and the fluctuation disappearance as the planetopause. These two boundaries limit the magnetosheath, where the expected increase in the level of turbulence is observed.

The Phobos 2 magnetic field observations show that the fluctuations which mark the boundary of the martian magnetosphere have an amplitude of typically 10 nT, and are observed over a few hundreds of kilometers on both side of the bow shock. They can therefore easily be detected on continuous recordings made onboard the lander during the descent phase, at a sampling rate of typically 20 vectors s-' and with an accuracy of a few tenth of nT.

4.3 The instrument

The proposed instrument is based on the magnetometer developed for the Mars 94 small stations (OPTIMISM/MAG experiment) and the German continental deep drilling 300°C project, which represents the state of the art instrument with ultra low power consumption and mass.

The basic configuration consists of two triaxial flux-gate magnetometer sensors, mounted remotely from the lander body on the boom of the crane used to install the seismometer. The orientation of the magnetic axis of the sensor with respect to the local geographic frame will be determinate by means of 2 axis tiltmeter and sun sensors installed on each of the magnetometer sensors.

4.3.1 The magnetometer

Ttre principle of operation of each component of the three-component magnetometer resembles that of the well-known flux-gate magnetometer: a highly permeable core is alternately saturated by a strong magnetic field in both preferential directions of magnetization. In a pick-up coil surrounding the core, an alternating voltage is thus induced. In the absence of external magnetic fields, this a.c. voltage will consist only of odd-numbered frequency components of the fundamental wave. If the system is exposed to an additional external magnetic field, even-numbered harmonics will also appear in the induced voltage. They are largely proportional to the external field, and they may be detected. The proportionality can be improved considerably by applying the principle of inverse feedback.

Contrary to the bar magnetic cores of flux-gate magnetometers, the one described here uses toroidal cores. Such cores are used very successfully particularly in space magnetometer experiments [projects: Magsat *(Acuña et al., 1978)*, Giotto *(Neubauer et al.,* 1986), and Mars Surveyor *(Acuña et al., 1992)]* They have the advantage of greater sensitivity, a lower zero-point drift, and lower noise. Because of their closed magnetic circuit, they require less exciter power than the strongly sheared bar cores. This means that they are more easily saturated.

First references to a magnetometer of this type can already be found in *Aschenbrenner and Goubau (1936).* They used florist's wire for their magnetic core! For the wide temperature range application desired here, nickel molybdenum permalloy cores with a diameter of 0.625 " and a Curie temperature of about 465 °C were chosen. The cores, which are equipped with a magnetization coil (exciter coil), are surrounded by the actual pick-up coils (measurement coils), which are flat rectangular coils. The latter consist of a thin-walled MACOR coil form, which supports the winding of enamel-coated copper wire. The temperature coefficient of MACOR (about 10 ppm) is about equal to that of the toroidal cores, so that even considerable temperature variations will not result in mechanical stresses.

Because the magnetometer is operated in the inverse feedback mode, each of these coils has dual functions: on one hand, it is used to detect the induced voltage, and on the other hand, to compensate the (magnetic) field in its interior, in the direction of its axis. Therefore the magnetic toroidal cores operate in a near-zero field. This causes the output signal, which is proportional to the field, to be linear over a wide measuring range. Conversely, by inverse feedback, the temperature stability of the instrument is mainly attributed to the mechanical stability of these coils. Each one of these units of toroidal core with pick-up coil is a magnetic probe, the measuring axis of which is identical to the longitudinal axis of the coil.

To measure the three dimensional magnetic field vector, three such units are required. They are mounted orthogonally to each other on a LEXAN-frame. Because of the inevitable extent of the individual probes, they can only be mounted with spatial displacements. The components are spaced approximatively 22 mm from each other.

The magnetometer electronics is quite similar to those of other space mission flux-gate circuitries. The main design goals were lowest power consumption, lowest possible mass, and wide temperature range (-1 00to+100 'C).

TABLE 1

Dynamic range:	±8192 nT
Quantization: (16 bits A/D)	±0.25 nT
Temperature drift: (+20/-120°C)	<0.1 $nT°K^{-1}$
Sensitivity (o to 0.1 Hz)	≈10^{-3} nT^2Hz^{-1}
Power consumption: (3 axis)	<200 mW
Mass: (sensor with housing)	I l o g

Performances of the OPTIMISM/MAG magnetometer,

Figure 4 presents examples of recordings made with the OPTIMISM magnetometer, and Table 1 summarizes the performances of this magnetometer. They show that this magnetometer is well suited to record magnetic variations with amplitude of few tens of nano-Teslas and typical variation time constants greater than 30 seconds, as it is expected to be the case on Mars.

4.3.2 Attitude restitution

The attitude restitution aims at determining the directions of the magnetic axes of the sensor with respect to the local geographic frame Rg (Geographic North, Geographic East, vertical posit ive downwards).

The attitude restitution will be made as follows:

- the direction of the magnetic axes of the sensor will be measured at the calibration facility, during calibration before launch; they will be referred to the sensor reference frame Rm;

- the direction of the local vertical will be measured at regular intervals by a set of two tiltmeters, during the time of normal operations on Martian ground;

- the direction of the Geographic North will be deduced from Solar angle measurements routinely made during surface operations.

In the case of the OPTIMISM/MAG experiment, the tiltmeters and the solar sensor are set on the magnetic sensor itself, allowing to refer directly the local geographic frame Rg to the magnetic frame Rm. The tiltmeters consist@ a sphere of about 1 cm in diameter, filled with a conductive liquid and having five electrodes. The resistance between the electrodes depends on the tilt of the instrument with respect to the local vertical. Measuring these resistances allows one to determine the direction of the local vertical. The solar angle measurements reduce to the determination of the instants at which the sun passes across three given planes that correspond to three slits in a black cover above a light detector.

5. SUMMARY

The magnetic field of a planet may have two primary sources, the convection in a conductive liquid core and the interaction between the planet and the solar wind. It may also result from secondary sources, the local magnetization of crustal lithospheric rocks and electric currents induced in the palnet by transient magnetic fields of external origin.

The depth of penetration of an electromagnetic wave in a conductive medium depends on both the period of the wave and the electrical resistivity of the medium. The larger the period and the resistivity, the greater the depth of penetration. Investigating the electrical strut-,J ture of the planet for depths ranging from, few hundreds of meters to few hundred of kilometers therefore requires to describe the magnetic variations for frequency ranging from a few tenths of second to a few sols.

Continuous recordings of the transient variations of the magnetic field at the surface of a planet will therefore provide information on both ifs inner structure and the electrodynamics of its ionized environment. The proposed experiment is to measure continuously during several months the transient variations of the magnetic field at the stations of the Intermarsnet network. The proposed instrument is based on the low-mass, low-power, precise, and very accurate three-component flux-gate magnetometers developed for the Mars 96 small stations (OPTIMISM/MAG experiment).

The anticipated results of this experiment can be summarized as follows:

1. conductive *structure of the planet:*

- thickness of the superficial layer of resistive permafrost;

- integrated conductivity of the basal layer of melt water, if any;

- resistivity profile below the landing sites, down to a few hundreds of kilometers;

- information about the relations between the inner structure of the planet and the surface geology;

2. *planetary field*

- information about the temporal (surface operations) and spatial (descent phase measurements) variations of the martian planetary field at the landing sites;

- constraints on the past and present martian dynamo;

3. *ionized environment*

- information about the ionosphere above the station, which would improve our knowledge of the electrodynamics of the martian environment;

- the intercomparison between recordings made at different latitudes at the surface of the planet on the one hand, and onboard the orbiter on the other hand, will provide information about the processes governing the interaction between the solar wind and the planetary environment.

Acknowledgements

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FIGURE CAPTIONS

Figure la

Magnetograms from the polar cap station Dumont D'Urville for two consecutive days having different activity levels [*Am* = 32, *Am* = 45, on January 6 and 7, 1986; see *Menvielle and Berthelier* (1991) for further details on the *Am* indices]. Local noon are indicated by circles. *(from Menvielle and Berthelier, 1991)*

Figure lb

Diurnal variation of H (or X) horizontal component of the Earth's magnetic field represented versus universal time (UT) for a chain of observatories having longitudes close to European ones. They are ordered according to geomagnetic latitude ranging from ≈5° (lower curve) to 88° (upper curve). Note the change in the scale between the lower (1 to 7) and upper (8 to 16) latitude stations *(after Kamide and Fukushima, 1972)*

Figure 1c

Variations of the Interplanetary Magnetic field during a 24 hour period.

Figure 2

Curves of resistivity versus temperature of suglinok permafrost for two cryogenous structures *(from Bogolyubov,* 1978). A - Massive texture; B - Streaky texture.

Figure 3

Variation of conductivity versus temperature and partial melting in peridotites and basalts at 15 and 30 kbar pressure. Curve W is from *Wyllie* (1971); curve R from *Ringwood (1975). (after Shank/and and Waff, 1977).*

Figure 4a

Example of recordings made with the OPTIMISM magnetometer in null field environment. The magnetic sensor is in a shielded box, inside the shielded room installed at the DT/INSU (Garchy, France) calibration facilities. The recorded variations are then an experimental example of the noise of the OPTIMISM magnetometer. Measurements are made at room temperature; they are digitized with a 24 bits A/D convertor (DU: 6.10' nT).

Figure 4b

Example of recordings of the transient variations of the Earth's magnetic field with the OPTIMISM magnetometer after compensation of the static magnetic field with the three axes Helmholtz coil system installed at the TU-BS (Braunschweig, Germany) calibration facilities. Measurements are made at room temperature; they are digitized with the *12* bits A/D OPTIMISM convertor (DU: 0.25 nT).

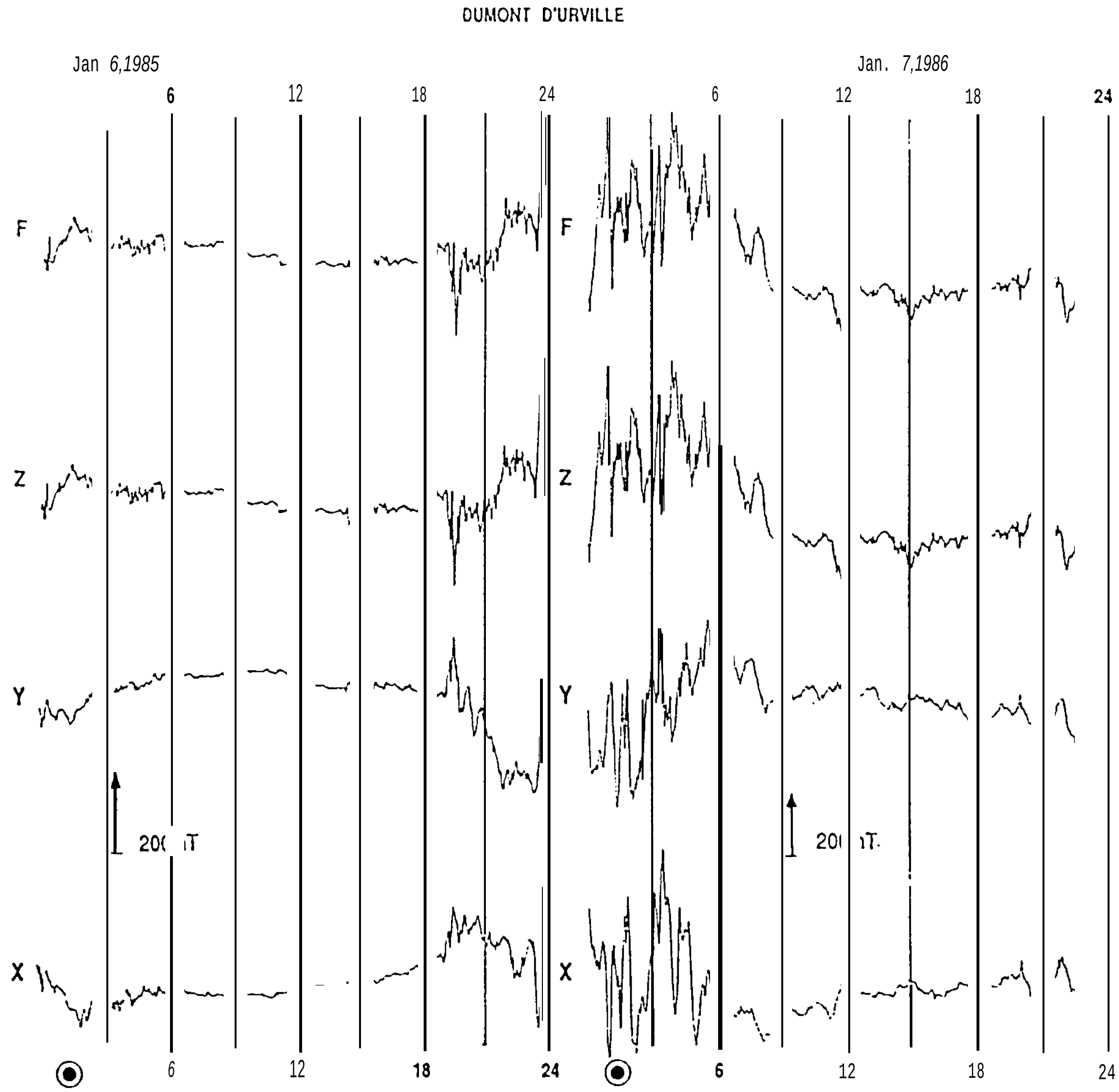

Figure 1 a

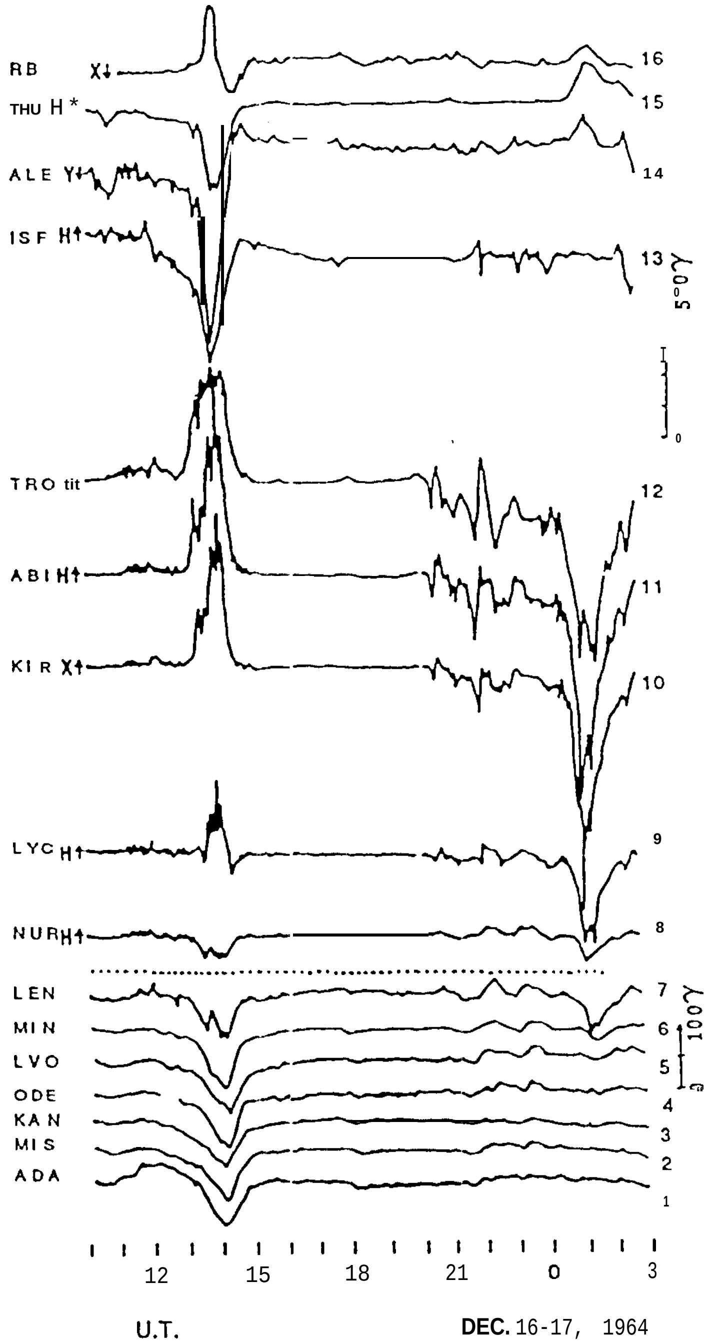
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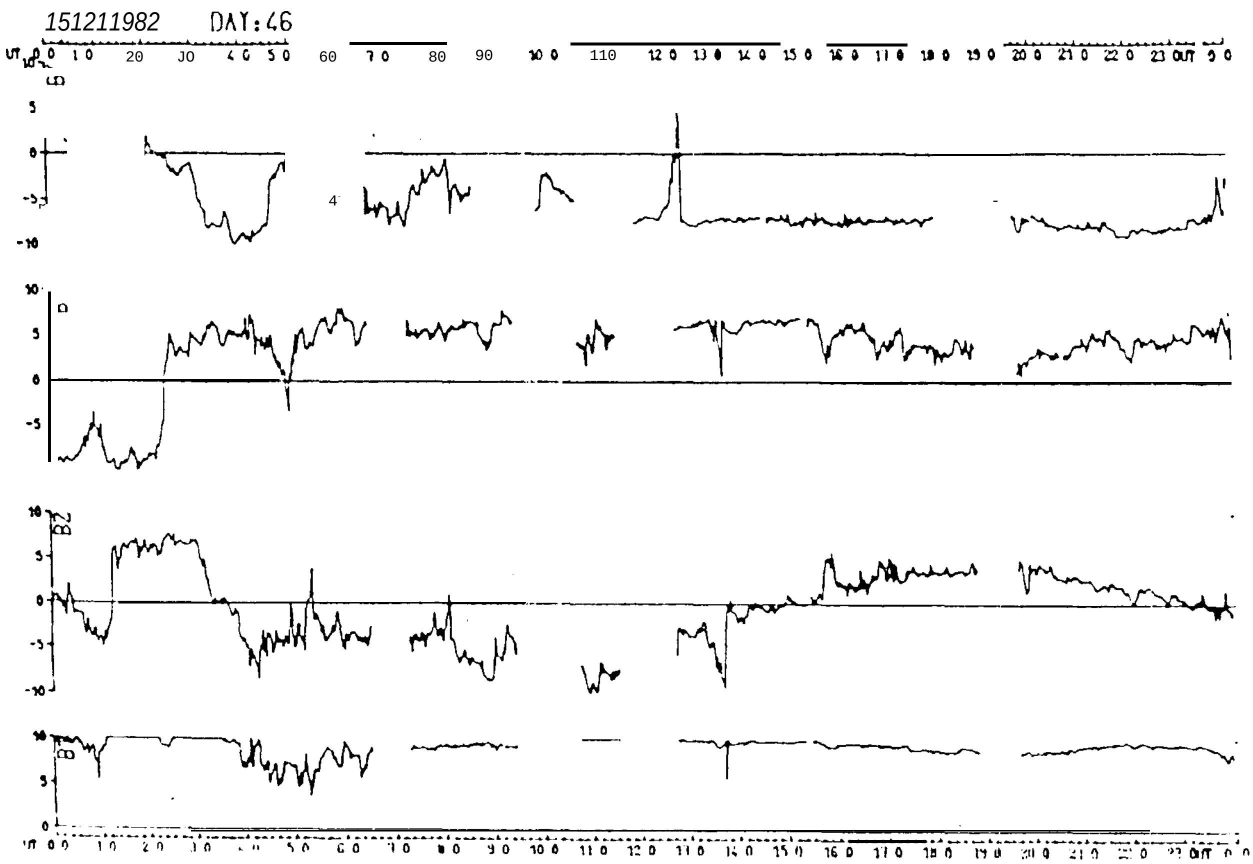
Figure 1b



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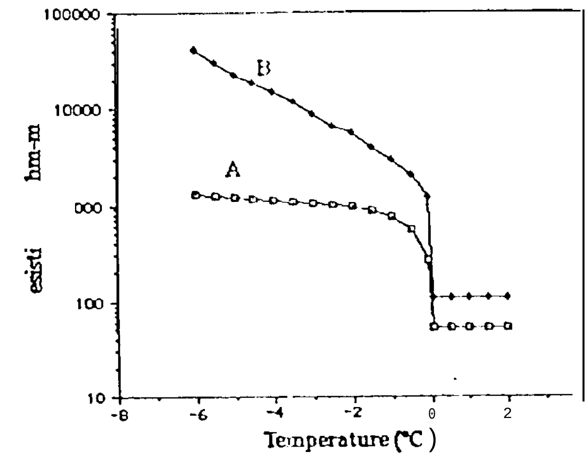
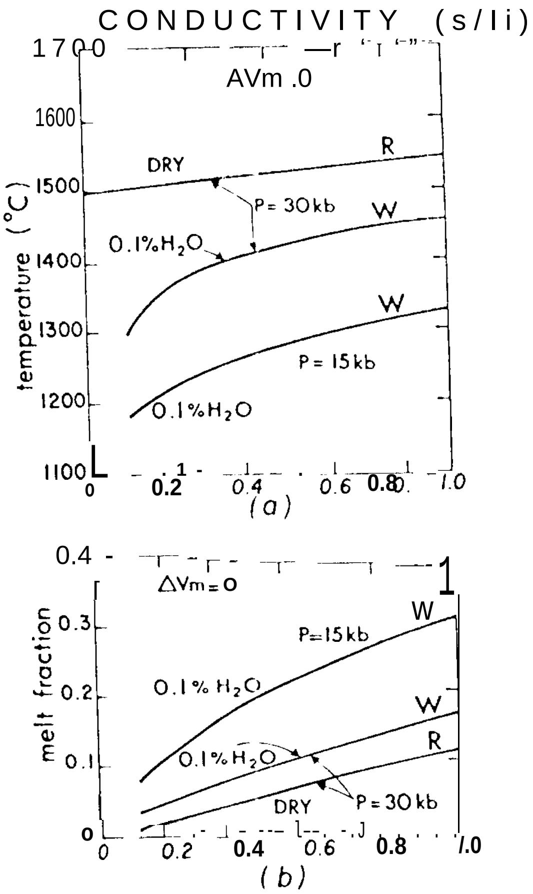


Figure 2.



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P = 15 kb
0.1% H_2O
temperature (°C)
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0.4
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0.4
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P=15 kb
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W
0.1% H_2O
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Figure 3

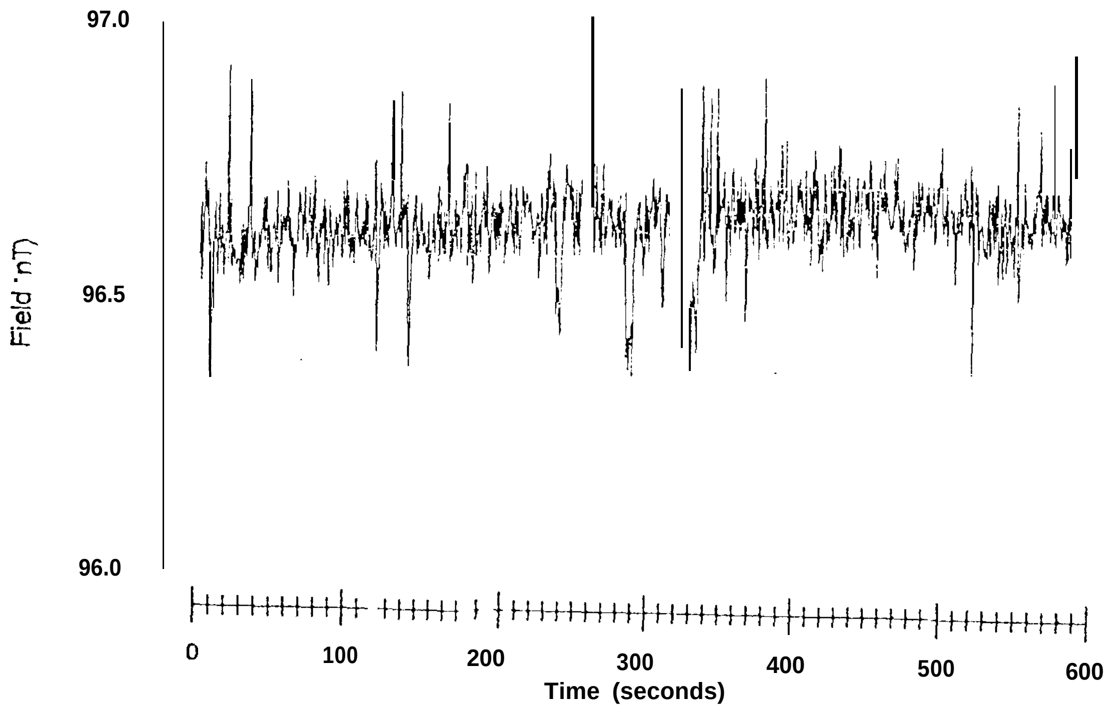
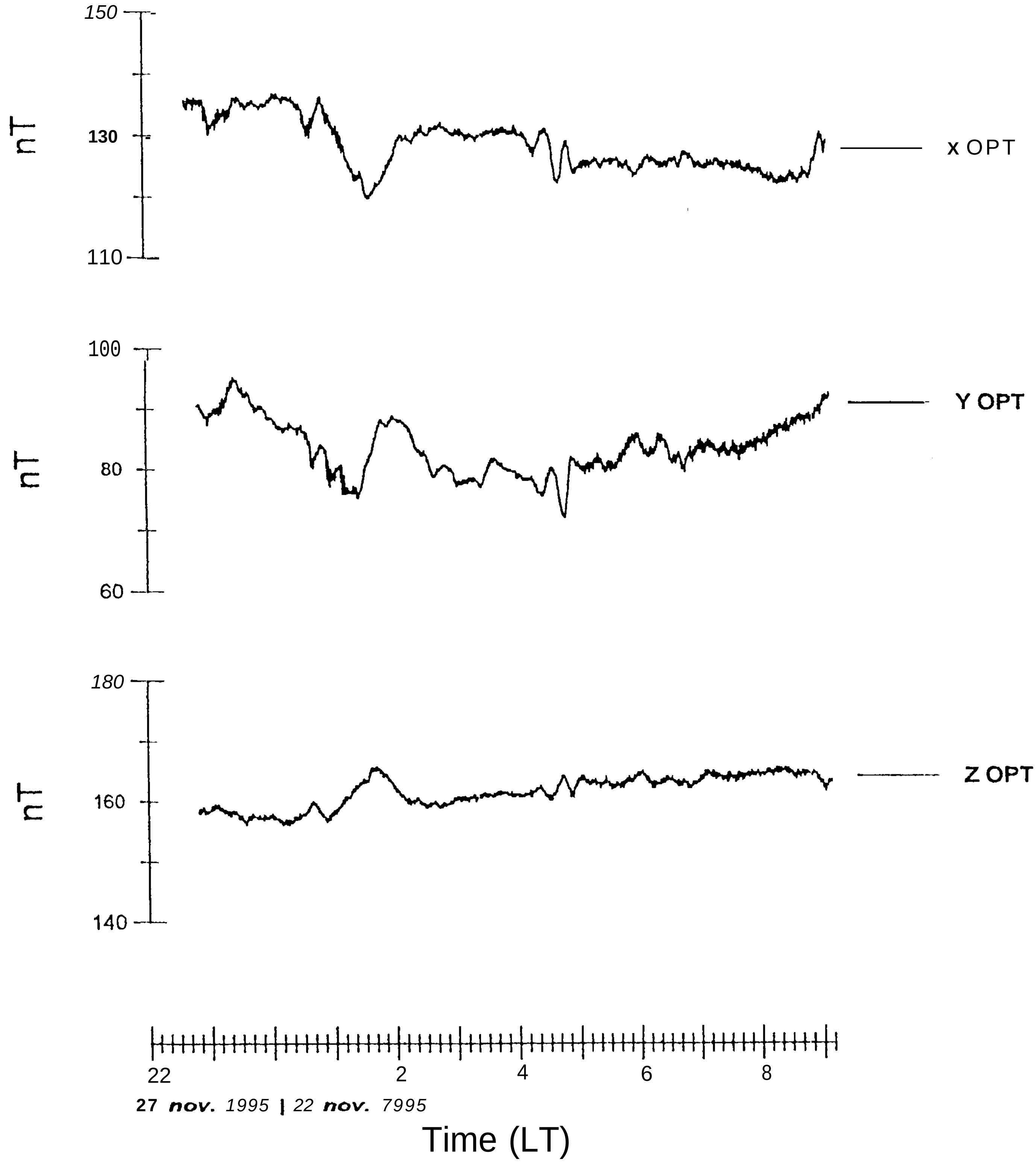


Figure 4a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Time (LT)

Figure 4b